Hadron Spectroscopy at LHCb

Claudia Patrignani
for the LHCb Collaboration

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA
CAMPUS DI RIMINI

Università di Bologna and I.N.F.N.
Claudia.Patrignani@bo.infn.it

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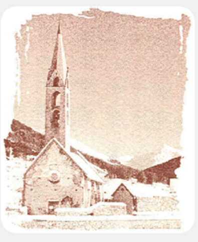
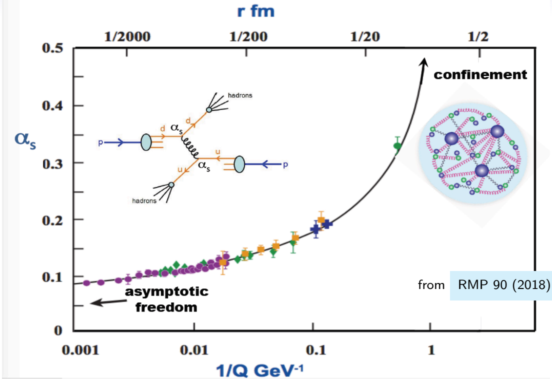


New and recent results on (mostly) heavy hadrons

- excited mesons
- excited charmed baryons, new beauty baryons, doubly heavy baryons,
- pentaquarks, charged charmonium-like states

Facts:

- QCD *is* part of the Standard Model



from RMP 90 (2018) 015003

unfortunately perturbative only at small distance

- many precision tests of Standard Model rely on controlling QCD corrections
- the primary observable of QCD is the hadron spectrum
- excited hadrons probe the region between long and short distance

The LHCb experiment

JINST 3 (2008) S08005

IJMP A30 (2015)1530022

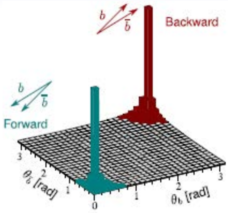
LHC has record numbers of b (and c) hadrons:

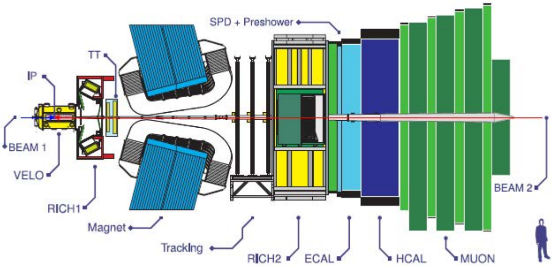
$\sigma_{b\bar{b}} \approx 250\ \mu\text{b}$ @ 7 TeV $\quad \sigma_{c\bar{c}} \approx 20 \times \sigma_{b\bar{b}}$

LHCb designed to study rare decays and CP violation in b-hadrons

ideal place also for spectroscopy

single-arm spectrometer covering the forward pseudorapidity region $2 < \eta < 5$



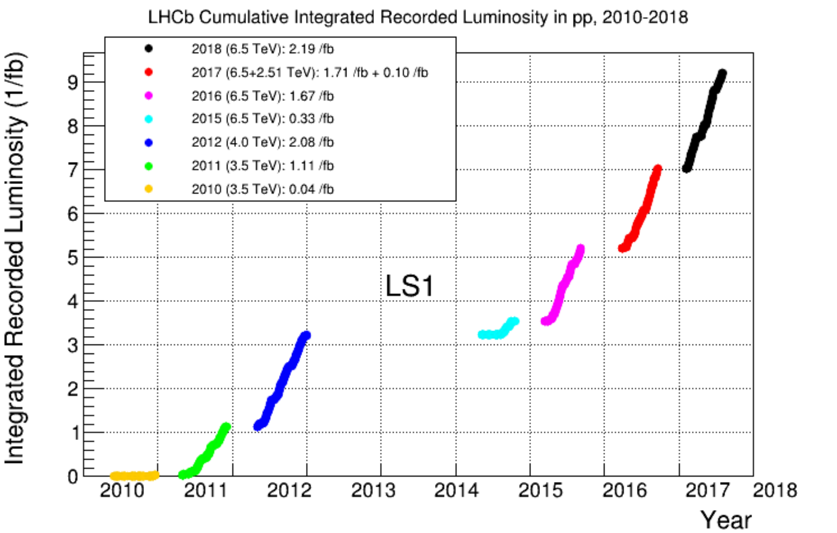


excellent performance:

- vertexing and tracking: good time of flight and invariant mass resolution
- PID for pions, kaons, protons and muons
- calorimeter

Trigger on high-p_t lepton or hadron from displaced vertexes

c and b-hadrons



Total integrated luminosity in *pp* collisions exceeds 9 fb^{-1}

results presented here mostly use less than half this

Amplitude analysis of $D^0 \to K^\mp\pi^\pm\pi^\pm\pi^\mp$

EPJC 78 (2018) 443

$D^0 \to K^\mp\pi^\pm\pi^\pm\pi^\mp$ decay amplitudes are required input for CKM angle γ and charm-mixing

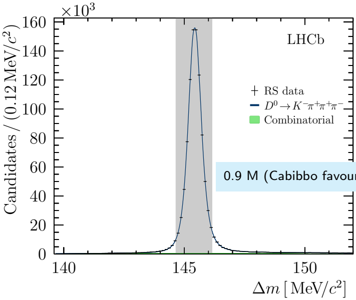
spectroscopy: higher K^* poorly known

Broad states, interference, thresholds... complicated!

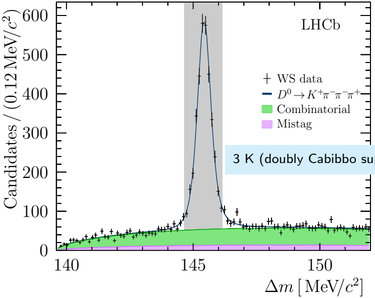
Strategy: very high purity D^0 sample selected with double tag:

7, 8 TeV; 3 fb^{-1}

$$\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu \quad \text{where} \quad D^{*+} \to D^0\pi^+$$



0.9 M (Cabibbo favoured)



3 K (doubly Cabibbo suppr.)

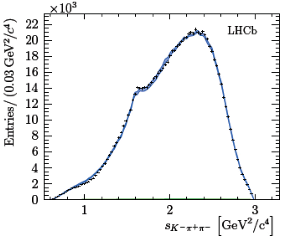
Amplitude analysis of $D^0 \to K^\mp\pi^\pm\pi^\pm\pi^\mp$

EPJC 78 (2018) 443

Resonance structure dominated by axial resonances:
fit fraction of $D^0 \to K_0(1460)^-\pi^+ \approx 4\%$

Quasi Model independent PWA of $K_0(1460)^-$:

$K(1460)^- \quad m_0 = 1482.40 \pm 3.58 \pm 15.22\,\mathrm{MeV}/c^2\ ;\ \Gamma_0 = 335.60 \pm 6.20 \pm 8.65\,\mathrm{MeV}/c^2$



Citation: M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018)

K(1460) $I(J^P) = \frac{1}{2}(0^-)$

OMITTED FROM SUMMARY TABLE
Observed in $K\pi\pi$ partial-wave analysis.

K(1460) MASS

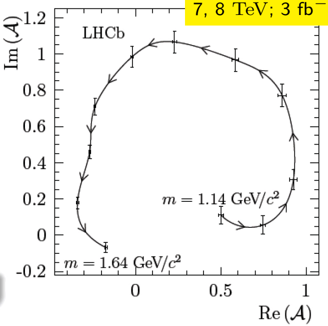
VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 1460	DAUM	81C	CNTR	−	63 $K^- p \to K^- 2\pi p$
~ 1400	[1] BRANDENB...	76B	ASPK	±	13 $K^\pm p \to K^+ 2\pi p$

[1] Coupled mainly to $K f_0(1370)$. Decay into $K^*(892)\pi$ seen.

K(1460) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 260	DAUM	81C	CNTR	−	63 $K^- p \to K^- 2\pi p$
~ 250	[2] BRANDENB...	76B	ASPK	±	13 $K^\pm p \to K^+ 2\pi p$

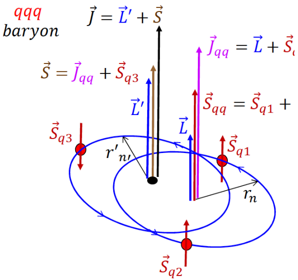
7, 8 TeV; 3 fb^{-1}



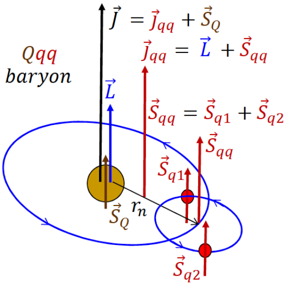
- Great potential to study light spectrum at LHCb

Baryon excitations

Also for baryons when at least one of the quarks is heavy the problem is simplified by the decoupling between heavy and light quark's spins

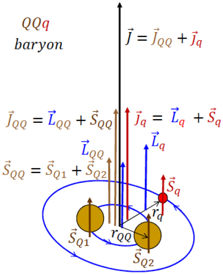


very complicated!



Heavy-light-light

$\Longrightarrow$light diquarks



Heavy-Heavy-light

$\Longrightarrow$heavy diquarks

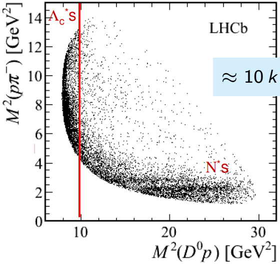
Heavy baryon excitations provide a keyhole into diquarks

JHEP05 (2017) 030

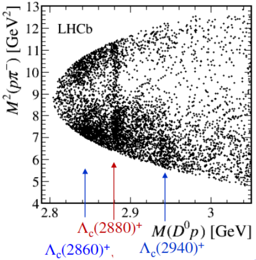
Excited Λ_c states

The D^0p amplitude needed for CKM angle γ in $\Lambda_b^0 \to D^0pK^-$

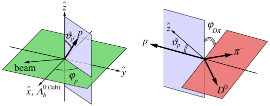
7, 8 TeV; 3 fb^{-1}



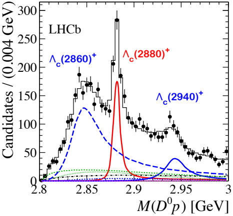
$\approx 10\,k\ \Lambda_b^0 \to D^0p\pi^-$



Λ_c^* and N^* are well separated



Angular analysis at low $M^2(D^0p)$



Determine $J^P = 1/2^+$ for $\Lambda_c(2940)^+$ and observe $\Lambda_c(2860)^+$ $[J^P = 3/2^+]$

$$m(\Lambda_c(2860)^+) = 2856.1^{+2.0}_{-1.7}(\text{stat}) \pm 0.5(\text{syst})^{+1.1}_{-5.6}(\text{model})\ \text{MeV},$$

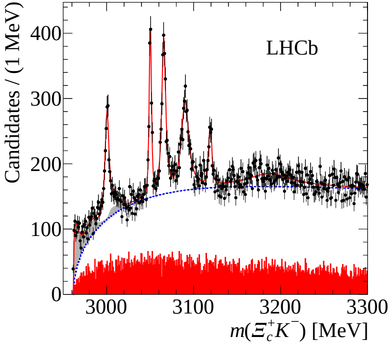
$$\Gamma(\Lambda_c(2860)^+) = 67.6^{+10.1}_{-8.1}(\text{stat}) \pm 1.4(\text{syst})^{+5.9}_{-20.0}(\text{model})\ \text{MeV}.$$

Five narrow excited Ω_c^0 states

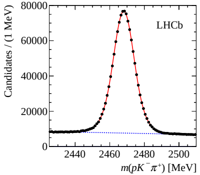
PRL 118 (2017)182001

7, 8, 13 TeV; 3.3 fb^{-1}

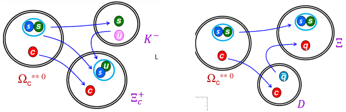
(css) Before: Only ground state Ω_c^0 $\left[J^P = \frac{1}{2}^+\right]$ and $\Omega_c(2770)^0$ $\left[J^P = \frac{3}{2}^+\right]$

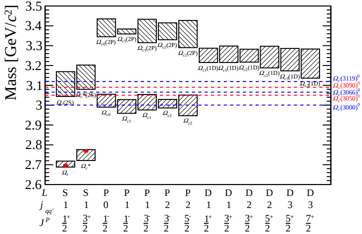


Five narrow peaks in $\Xi_c^+ K^-$ from $\approx 1M$ $\Xi_c^+ \to pK^-\pi^+$



Narrowness below ΞD threshold hints at diquark





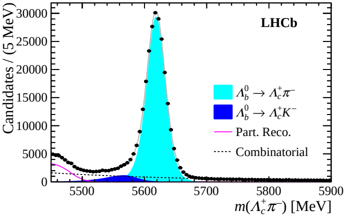
Masses within range of predictions

PRL 122 (2019) 012001

7, 8 TeV; 3 fb^{-1}

$\Sigma_b^{\pm}$ and $\Sigma_b^{*\pm}$ masses and widths

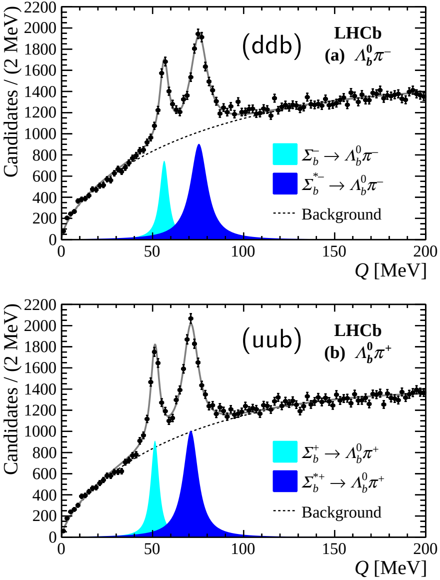
pair large Λ_b^0 samples with $\pi^{\pm}$



fit $Q = m(\Lambda_b^0\pi^{\pm}) - m(\Lambda_b^0) - m(\pi^{\pm})$

to obtain precise determination of masses and widths (in MeV)

$m(\Sigma_b^-)$	$5815.64 \pm 0.14 \pm 0.24$
$m(\Sigma_b^{*-})$	$5834.73 \pm 0.17 \pm 0.25$
$m(\Sigma_b^+)$	$5810.55 \pm 0.11 \pm 0.23$
$m(\Sigma_b^{*+})$	$5830.28 \pm 0.14 \pm 0.24$
$\Gamma(\Sigma_b^-)$	$5.33 \pm 0.42 \pm 0.37$
$\Gamma(\Sigma_b^{*-})$	$10.68 \pm 0.60 \pm 0.33$
$\Gamma(\Sigma_b^+)$	$4.83 \pm 0.31 \pm 0.37$
$\Gamma(\Sigma_b^{*+})$	$9.34 \pm 0.47 \pm 0.26$



Observation of $\Sigma_b(6097)^-$ and $\Sigma_b(6097)^+$

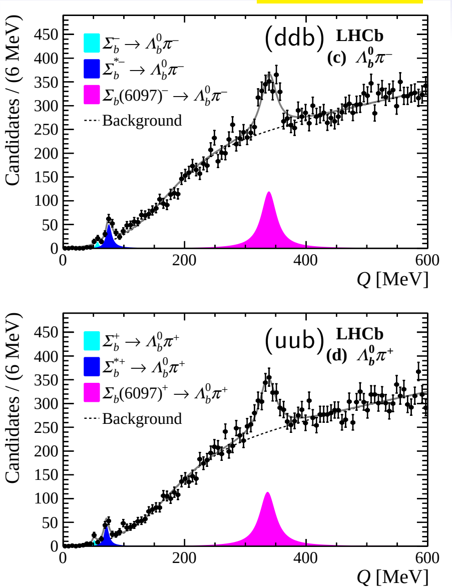
PRL 122 (2019) 012001

7, 8 TeV; 3 fb^{-1}

Al larger value of
$$Q = m(\Lambda_b^0\pi^\pm) - m(\Lambda_b^0) - m(\pi^\pm)$$
two new states (significance $> 12\,\sigma$)

Quantity	Value [MeV]
$m(\Sigma_b(6097)^-)$	$6098.0 \pm 1.7 \pm 0.5$
$m(\Sigma_b(6097)^+)$	$6095.8 \pm 1.7 \pm 0.4$
$\Gamma(\Sigma_b(6097)^-)$	$28.9 \pm 4.2 \pm 0.9$
$\Gamma(\Sigma_b(6097)^+)$	$31.0 \pm 5.5 \pm 0.7$

Compatible with being two of the 5 $\Sigma_b(1P)$ states expected in that mass range



PRL 121 (2018) 072002

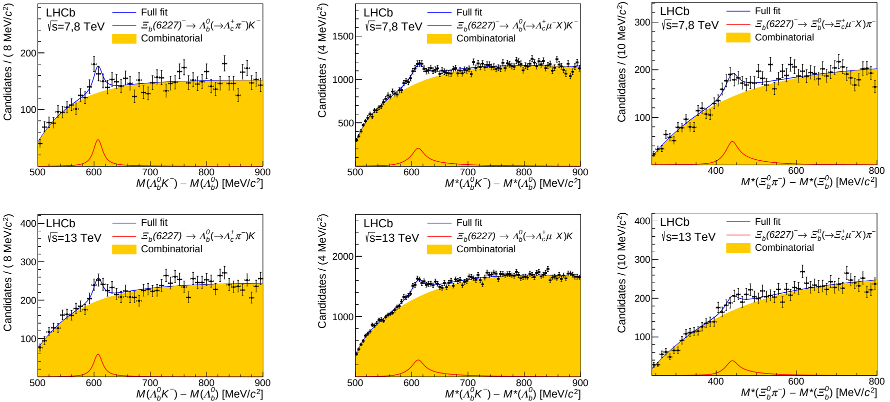
7, 8, 13 TeV; 4.5 fb^{-1}

Observation of $\Xi_b(6227)^{**-}$

Observed in two decay modes

$\Xi_b^{**-} \to \Lambda_b^0 K^-$ — $\Lambda_b^0 \to \Lambda_c^+ \pi^-$; $\Lambda_b^0 \to \Lambda_c^+ \mu^- X$

$\Xi_b^{**-} \to \Xi_b^0 \pi^-$ — $\Xi_b^0 \to \Xi_c^+ \mu^- X$



$$M(\Xi_b^{**-}) - M(\Lambda_b^0) = 607.3 \pm 2.0\,(\text{stat}) \pm 0.3\,(\text{syst})\ \text{MeV}/c^2,$$

$$\Gamma = 18.1 \pm 5.4\,(\text{stat}) \pm 1.8\,(\text{syst})\ \text{MeV}/c^2,$$

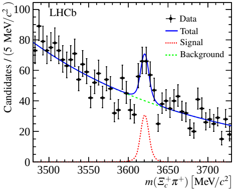
$$M(\Xi_b^{**-}) = 6226.9 \pm 2.0\,(\text{stat}) \pm 0.3\,(\text{syst}) \pm 0.2(\Lambda_b^0)\ \text{MeV}/c^2,$$

Mass peak position is consistent between the three decay channels

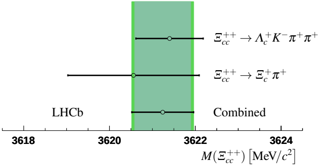
Doubly charm baryon: Ξ_{cc}^{++}

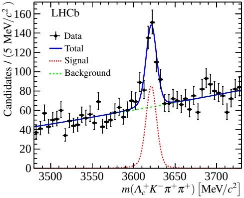
Doubly charmed Ξ_{cc}^{+} reported by SELEX in $\Lambda_c^+ K^- \pi^+$ PRL 89 (2002) 112001 and pD^+K^- PLB 628 (2005) 18 never confirmed

Observation of $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ **PRL 119 (2017) 112001**



and now confirmed with larger statistic also in $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$ **PRL 121 (2018) 162002**
at compatible mass 13 TeV; 1.7 fb^{-1}



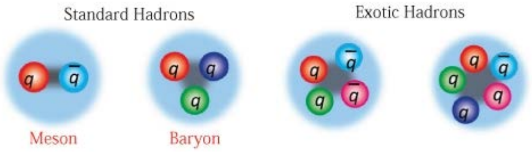


also: first measurement of lifetime **PRL 121 (2018) 052002** 13 TeV; 1.7 fb^{-1}

$$\tau(\Xi_{cc}^{++}) = (0.256\,^{+0.024}_{-0.022} \pm 0.014)\,\text{ps}$$

Standard and Exotic Hadrons

Mesons and baryons with other than $q\bar{q}$ or qqq configurations are not forbidden by QCD (as long as they remain colour-less)



Their possibility admitted as early as the quark model was introduced

Volume 8, number 3 PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 6) q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest baryon configuration $(q\,q\,q)$ gives just the representations **1**, **8**, and **10** that have been observed, while

8419/TH.412
21 February 1964

AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

II *)

G. Zweig **)
CERN---Geneva

*) Version I is CERN preprint 8182/TH.401, Jan. 17, 1964.

6) In general, we would expect that baryons are built not only from the product of three aces, AAA, but also from $\bar{A}AAAA$, $\bar{A}\bar{A}AAAAA$, etc., where $\bar{A}$ denotes an anti-ace. Similarly, mesons could be formed from $\bar{A}A$, $\bar{A}\bar{A}AA$ etc. For the low mass mesons and baryons we will assume the simplest possibilities, $\bar{A}A$ and AAA, that is, "deuces and treys".

no undisputed evidence yet in light hadrons

Exotic or not?

How can you tell if a state is exotic?

not easy and not always straightforward!

Manifestly exotic

- quantum numbers not allowed for $q\bar{q}'$ or $qq'q''$
- >3 valence quarks required

Undisputed

(but many possible exotic states would not fall in this definition)

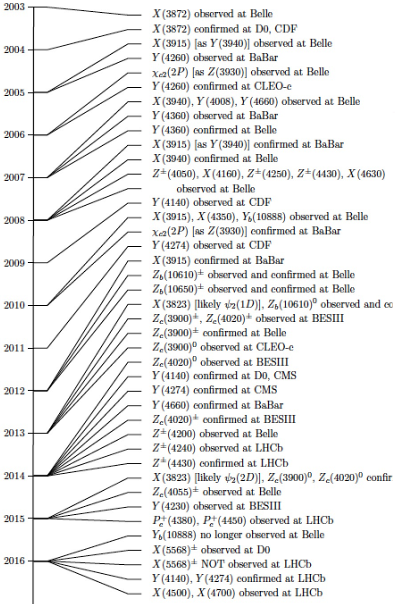
"Cryptoexotic"

- quantum numbers allowed also for $q\bar{q}'$ or $qq'q''$
- mass/width not fitting in conventional meson or baryon spectra
- overpopulation of the spectra

  which is "standard" / "exotic"?
- production or decay properties incompatible with standard mesons/baryons

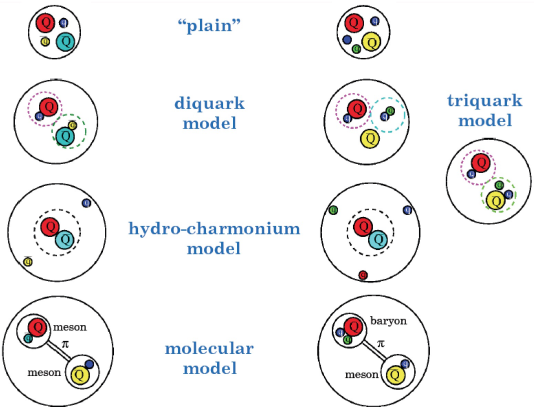
...endless disputes..

Exotic hadrons with heavy quarks



in the past decade a pletora of new states with constituent heavy $Q\bar{Q}$

which is their structure?



Most of them "cryptoexotic"

a few manifestly exotic

Earlier LHCb results on tetraquarks (and tetraquark candidates)

- $\chi_{c1}(3872)$ aka $X(3872)$:
  - quantum numbers PRL 110, 222001 (2013)
  - Mass (and limit on width)
  - radiative decays NP B886 (2014) 665
  - p_t dependence of prompt production EPJC 72 (2012) 1972
  - other decay modes? exclusive production in other than $B^{\pm}$? PLB 769 (2017) 305
- $Z_c(4430)^+$
  - confirmed with both amplitude analysis PRL 112 (2014)222002 and model independent approach PRD 92 (2015) 112009
  - resonant behaviour
  - quantum numbers
- $B^+ \to J/\psi\,\phi K^+$
  - 4 $J/\psi\,\phi$ structures PRL 118 (2017) 022003 PRD 95 (2017) 012002

Earlier LHCb results on pentaquarks

- Observation of $P_c(4450)^{\pm}$ and $P_c(4380)^{\pm} \to J/\psi\, p$ in $\Lambda_b^0 \to J/\psi\, pK^-$ from both amplitude analysis PRL 115 (2015) 072001 and model independent approach PRL 117(2016)082002
  - $c\bar{c}uud \Longrightarrow$ pentaquark!
  - resonant behaviour of $P_c(4450)^{\pm}$ amplitude
  - resonant behaviour inconclusive for $P_c(4380)^{\pm}$
- Evidence for exotic hadrons in $\Lambda_b^0 \to J/\psi\, p\pi^-$ PRL 117 (2016) 082003
  - compatible with P_c states in different decay mode
  - amplitude analysis limited by sample size
- observation of new Λ_b^0 decay modes to charmonia : $\Lambda_b^0 \to \chi_c pK^-$ PRL 119 (2017) 062001 and $\Xi_b^- \to J/\psi\, \Lambda K^-$ PL B772 (2017) 265
  - possible modes where to search for new $P_c(4450)$ decay modes and search for further pentaquarks
  - might have sufficient statistics for amplitude analysis by the end of upcoming data taking

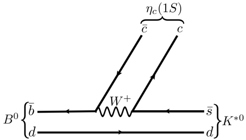
EPJC 78 (2018) 1019

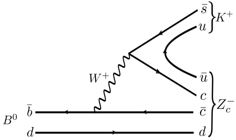
Search for exotics in $B^0 \to \eta_c(1S)\pi^- K^+$

A number of predictions for resonances in $\eta_c(1S)\pi^-$

- hadrocharmonium: $M \approx 3800\ \mathrm{MeV}/c^2$ Voloshin, PRD 87 (2013) 091501
- quarkonium hybid: $J^P = 0^+, 1^-, 2^+$ with $M \approx 4025, 3770, 4045$ Liu et al., JHEP 07 (2012)126
  Cheung et al., JHEP 12 (2016) 089
- diquark model $J^P = 0^+$ and $M < 3770$ Maiani et al., PRD 71 (2005) 014028

Could be produced in B decays, similarly to $Z_c(4430)^-$





Important to understand exotic hadrons with hidden charm in particular the $Z_c(3900)^- \to J/\psi\,\pi^-$ reported by BESIII

PRL 110 (2013) 252001

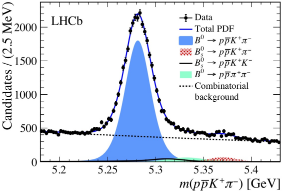
Evidence for $\eta_c(1S)\pi^-$ resonance in $B^0 \to \eta_c(1S)\pi^- K^+$ with $\eta_c(1S) \to p\bar{p}$

EPJC 78 (2018) 1019

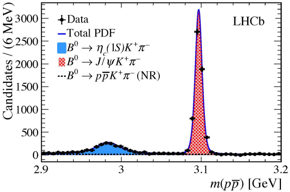
7, 8, 13 TeV; 4.7 fb^{-1}

Exploit LHCb particle ID to reconstruct clean samples of events

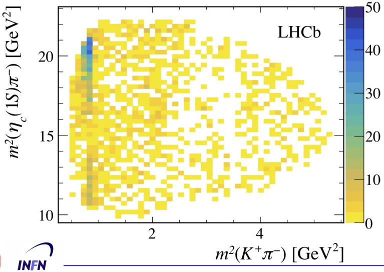
30 k $B^0 \to p\bar{p}\pi^- K^+$



2.1 k $B^0 \to \eta_c(1S)\pi^- K^+$



$B^0 \to \eta_c(1S)\pi^- K^+$



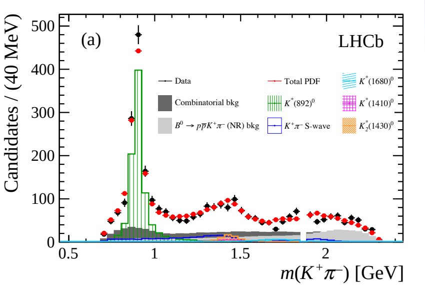
Fit to the Dalitz plot with and without exotic component

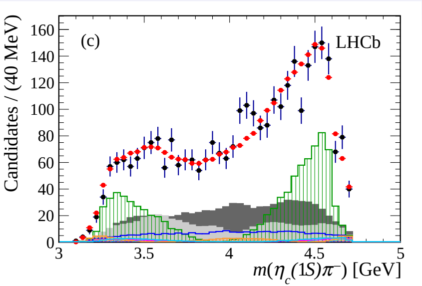
- take into account $\Gamma(\eta_c(1S)) \approx 32$ MeV
- isobar model for decay amplitude coherent sum of $K^+\pi^-$ resonant and non-resonant
- LASS model for $K^+\pi^-$ S-wave

Fit with only $K^-\pi^+$ contributions

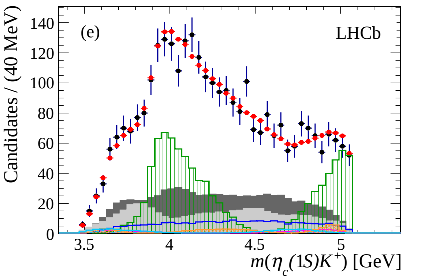
EPJC 78 (2018) 1019

7, 8, 13 TeV; 4.7 fb^{-1}





Resonance	Mass [MeV]	Width [MeV]	J^P	Model
$K^*(892)^0$	895.55 ± 0.20	47.3 ± 0.5	1^-	RBW
$K^*(1410)^0$	1414 ± 15	232 ± 21	1^-	RBW
$K_0^*(1430)^0$	1425 ± 50	270 ± 80	0^+	LASS
$K_2^*(1430)^0$	1432.4 ± 1.3	109 ± 5	2^+	RBW
$K^*(1680)^0$	1717 ± 27	322 ± 110	1^-	RBW
$K_0^*(1950)^0$	1945 ± 22	201 ± 90	0^+	RBW

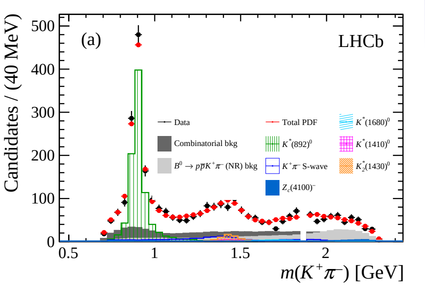


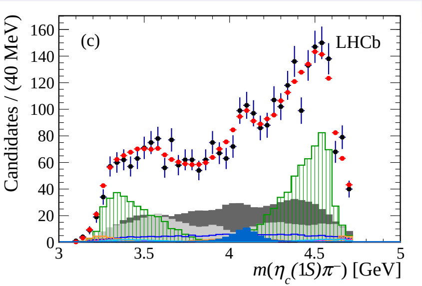
The $K\pi$ resonances describe well the data almost everywere except around $M(\eta_c\pi) \approx 4.1$ GeV

EPJC 78 (2018) 1019

7, 8, 13 TeV; 4.7 fb^{-1}

Fit with $K^-\pi^+$ and exotic contributions



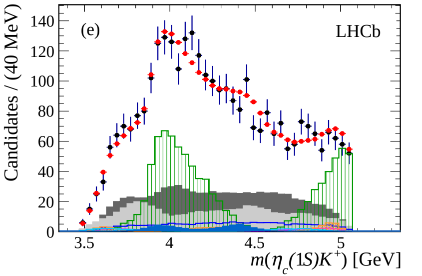


Exotic component with $J^P = 0^+$ or 1^- to adequately describe data

Significance, including systematic, exceeds $3\,\sigma$ ($4.8\,\sigma$ stat. only)

$$M = 4096 \pm 20^{+18}_{-22}\ \text{MeV}$$

$$\Gamma = 152 \pm 58^{+60}_{-35}\ \text{MeV}$$



Other results on $B^0 \to \eta_c(1S)\pi^- K^+$

EPJC 78 (2018) 1019

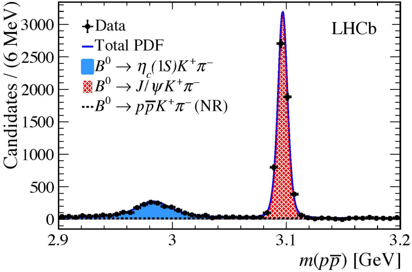
7, 8, 13 TeV; 4.7 fb^{-1}

First measurement of

$$\mathcal{B}(B^0 \to \eta_c(1S)K^+\pi^-) = (5.73 \pm 0.24 \pm 0.13 \pm 0.66) \times 10^{-4}$$

over the whole $K^+\pi^-$ inv. mass. range

Branching ratios normalized to $B^0 \to J/\psi\pi^- K^+$



the fit fractions for the $K^+\pi^-$ components are also measured

Amplitude	Fit fraction (%)
$B^0 \to \eta_c K^*(892)^0$	$51.4 \pm 1.9\ ^{+1.7}_{-4.8}$
$B^0 \to \eta_c K^*(1410)^0$	$2.1 \pm 1.1\ ^{+1.1}_{-1.1}$
$B^0 \to \eta_c K^+\pi^-$ (NR)	$10.3 \pm 1.4\ ^{+1.0}_{-1.2}$
$B^0 \to \eta_c K_0^*(1430)^0$	$25.3 \pm 3.5\ ^{+3.5}_{-2.8}$
$B^0 \to \eta_c K_2^*(1430)^0$	$4.1 \pm 1.5\ ^{+1.0}_{-1.6}$
$B^0 \to \eta_c K^*(1680)^0$	$2.2 \pm 2.0\ ^{+1.5}_{-1.7}$
$B^0 \to \eta_c K_0^*(1950)^0$	$3.8 \pm 1.8\ ^{+1.4}_{-2.5}$
$B^0 \to Z_c(4100)^- K^+$	$3.3 \pm 1.1\ ^{+1.2}_{-1.1}$

Search for beautiful tetraquarks

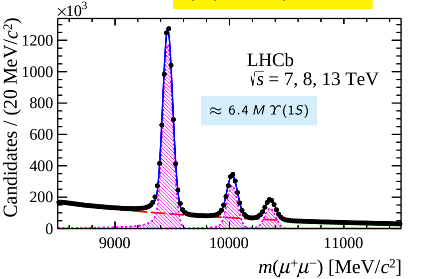
JHEP 10 (2018) 086

7, 8,13 TeV; 6.3 fb^{-1}

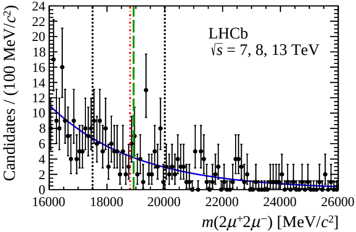
Numerous predictions for $(b\bar{b}\,b\bar{b})$ tetraquarks with $M \approx 18.4 - 18.8$ GeV (below $\eta_b\eta_b$)

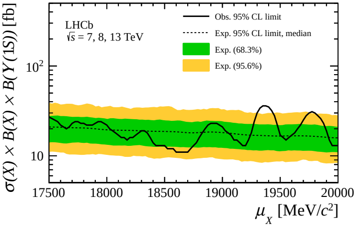
$\Longrightarrow$ could decay to $\Upsilon(1S)\mu^+\mu^-$

LHCb has large samples of $\Upsilon(1S) \to \mu^+\mu^-$



No signal observed in invariant mass of $\mu^+\mu^-$ paired to $\Upsilon(1S)$ candidates





UL on $\sigma(pp \to X) \times \mathcal{B}(X \to \Upsilon(1S)\mu^+\mu^-) \times \mathcal{B}(\Upsilon(1S) \to \mu^+\mu^-)$

Conclusions

LHCb has proved a treasure trove for heavy hadrons spectroscopy in every field

Just a few of the recent results

- $K_0(1460)^-$ from amplitude analysis of $D^0 \to K^{\mp}\pi^{\pm}\pi^{\pm}\pi^{\mp}$
- 5 new narrow excited Ω_c^0 states
- Precise $\Sigma_b^{\pm}$ and $\Sigma_b^{*\pm}$ masses and widths and observation of $\Sigma_b(6097)^-$ and $\Sigma_b(6097)^+$
- Observation of $\Xi_b(6227)^{**-}$
- Observation of Ξ_{cc}^{++} in two decay modes and measurement of its lifetime
- Evidence for exotic $\eta_c(1S)\pi^-$ resonance in $B^0 \to \eta_c(1S)\pi^- K^+$
- Search for beautiful tetraquark

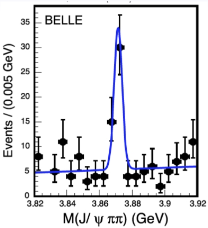
Still a lot to understand – and a lot of data at LHC!

already on disk and more in the near future

Extra slides

The $\chi_{c1}(3872)$ aka $X(3872)$

PRL 91 (2003) 262001



Discovered by Belle as a narrow peak in $J/\psi\pi^+\pi^-$ invariant mass in $B^+ \to (J/\psi\pi^+\pi^-)K^+$ decays.

Well above open charm threshold

... yet very narrow: $\Gamma < 1.2\,\mathrm{MeV}$

– mass amazingly close to the $D^0 - D^{*0}$ threshold

loosely bound $D - D^*$ molecule?

– radiative decays to $J/\psi\,\gamma \implies C = +$

– $J/\psi\,\pi^+\pi^-$ compatible with $J/\psi\,\rho$, yet significant $J/\psi\,\pi^+\pi^-\pi^0$ $(J/\psi\,\omega)$

I-spin violation?

– prompt production in $p\bar{p}$ and pp at similar rates as $c\bar{c}$

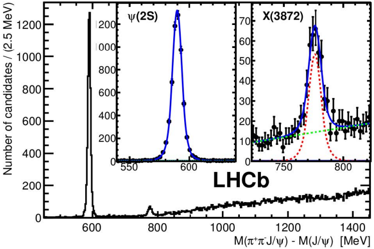
Extremely difficult to identify as a conventional charmonium state, but some of its properties look like charmonium

Determination of the $\chi_{c1}(3872)$ quantum numbers

CDF PRL 98 (2007) 132002 , Belle PRD 85 (2012) 052003 , *BABAR* PRD 82 (2010) 011101

1D angular distribution – all J^{PC} assignments excluded except 1^{++} or 2^{-+}

LHCb: **PRL 110, 222001 (2013)**

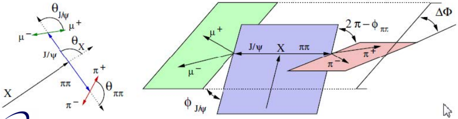


5D angular analysis of

$$B^+ \to K^+ \chi_{c1}(3872) \to K^+ J/\psi \pi^+ \pi^-$$

Angular correlations in the B^+ decay chain carry information on the J^{PC} of the $\chi_{c1}(3872)$

$$\Omega = (\cos\theta_X, \cos\theta_{\pi\pi}, \Delta\phi_{X,\pi\pi}, \cos\theta_{J/\psi}, \Delta\phi_{X,J/\psi})$$



Matrix elements in the helicity formalism

$J^{PC} = 1^{++}$

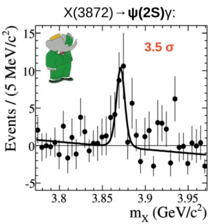
$\chi_{c1}(3872)$ radiative decays

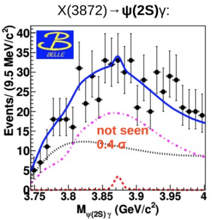
PRL 102(2009) 132001 PRL 107 (2011) 091803

Predictions:

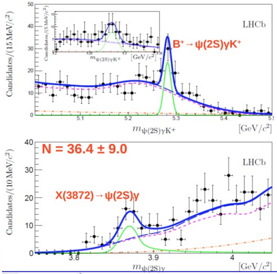
$\mathcal{B}(\psi(2S)\gamma) \approx 0$ for purely molecular state

inconclusive results from B-factories



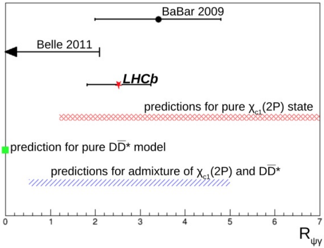


LHCb: NP B886 (2014) 665



$$R_{\psi\gamma} = \frac{\mathcal{B}(X(3872) \to \psi(2S)\gamma)}{\mathcal{B}(X(3872) \to J/\psi\gamma)} = 2.46 \pm 0.64 \pm 0.29$$

(stat) (syst)



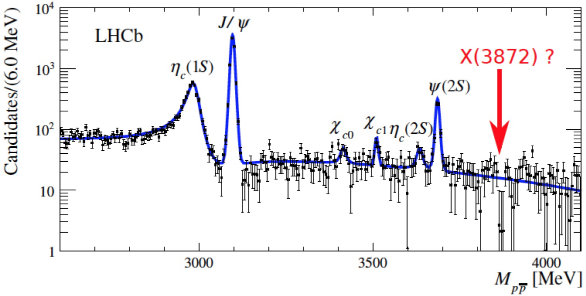
$\chi_{c1}(3872) \to p\bar{p}$?

$\mathcal{B}(\chi_{c1}(3872) \to p\bar{p})$: predictions for regular charmonia larger (usually) than for other interpretations

Prospects for $\chi_{c1}(3872)$ of PANDA or other $p\bar{p}$ formation experiments depend on its value

$B^+ \to K^+ p\bar{p}$

PL B769 (2017) 305



$$\frac{\mathcal{B}(B^+ \to X(3872)K^+) \times \mathcal{B}(X(3872) \to p\bar{p})}{\mathcal{B}(B^+ \to J/\psi K^+) \times \mathcal{B}(J/\psi \to p\bar{p})} < 0.25 \times 10^{-2}$$ @ 95% CL

also: measurements of $\eta_c(2S) \to p\bar{p}$, mass and width of $\eta_c(1S)$

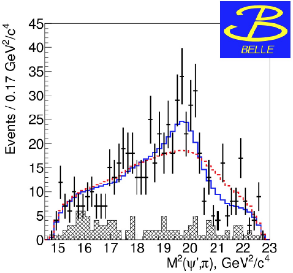
$Z_c(4430)^+$

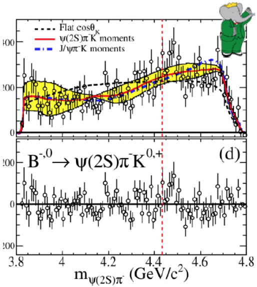
Discovered by Belle in $B^0 \to \psi(2S)\pi^- K^+$

PRL 100 (2008) 142001

PRD 80 (2009) 031104

PRD 88 (2013) 074026



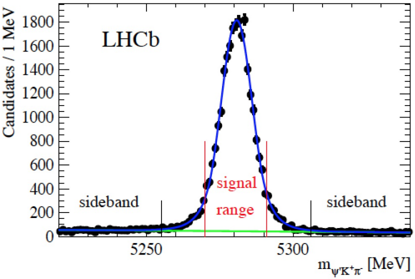


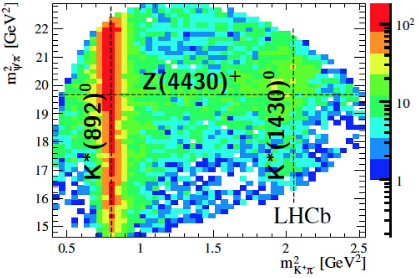
not confirmed by *BABAR* PRD79 (2009) 112001

manifestly exotic: no charged standard mesons with valence $c\bar{c}$

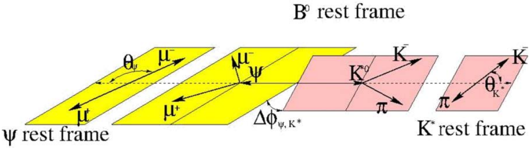
$Z_c(4430)^+$ in $B^0 \to \psi(2S)K^+\pi^-$ at LHCb

$\approx$ 25k $B^0 \to \psi(2S)K^+\pi^-$ with $\approx$ 4% combinatorial background

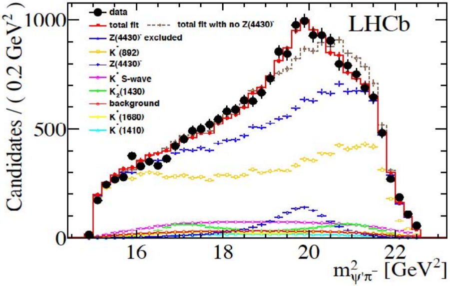


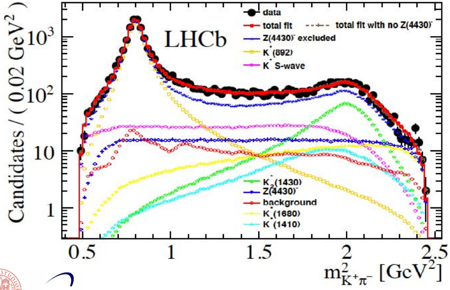


perform 4D amplitude analysis PRL 112 (2014)222002



$Z_c(4430)^+$ in $B^0 \to \psi(2S)K^+\pi^-$ at LHCb



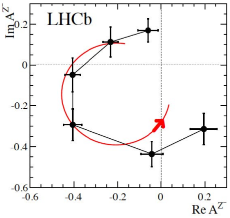


PRL 112 (2014)222002

$$M = 4475 \pm 7^{+15}_{-25}\ \mathrm{MeV}/c^2$$

$$\Gamma = 172 \pm 13^{+37}_{-34}\ \mathrm{MeV}$$

- $J^P = 1^+$
- Argand plot shows resonant behaviour



Model independent confirmation of $Z_c(4430)^+$ in $B^0 \to \psi(2S)K^+\pi^-$

PRD 92 (2015) 112009

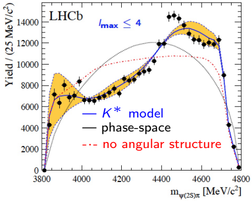
Check that $K^-\pi^+$ amplitudes only fail to describe the decay

K* resonances should contribute to low angular moments, while exotic $\psi\pi$ would contribute to all moments

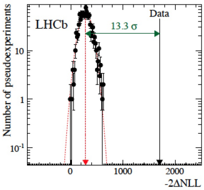
Allow relative angular momenta up to ℓ_{max} and compare to unreasonably large $\ell_{max} = 30$

$\ell_{max} \leq 4$

(S, P and D waves)

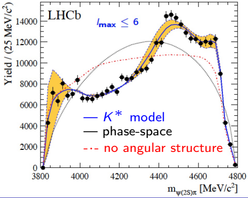


full $m_{K\pi}$ spectrum

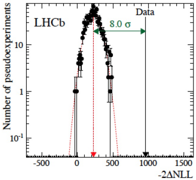


$\ell_{max} \leq 6$

(S, P, D and F waves)



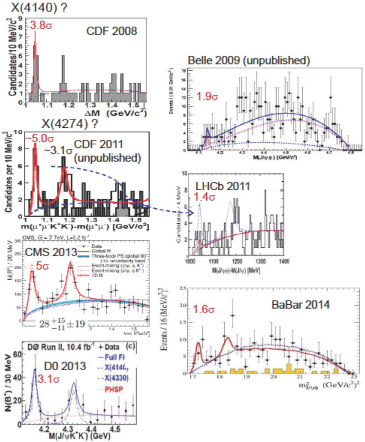
full $m_{K\pi}$ spectrum

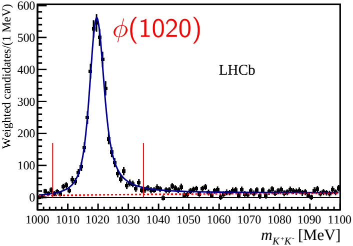


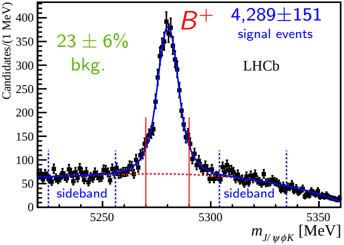
Exotic(?) states $X \to J/\psi\,\phi$?

PRL 118 (2017) 022003
PRD 95 (2017) 012002

Many experiments reported states decaying to $J/\psi\phi$:
$X(4140)$ and/or other higher mass states in B decays, but also $\gamma\gamma$, double $c\bar{c}$.





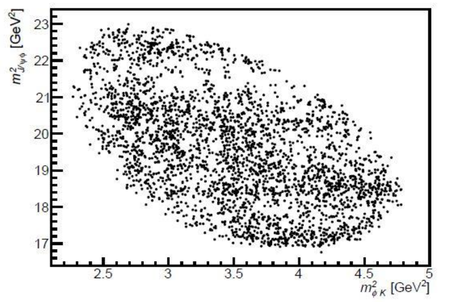


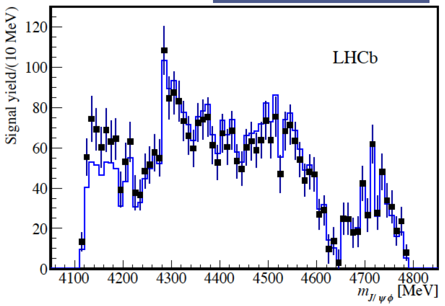
The LHCb sample of $B^+ \to J/\psi\,\phi K^+$ from Run1 is the largest analysed so far

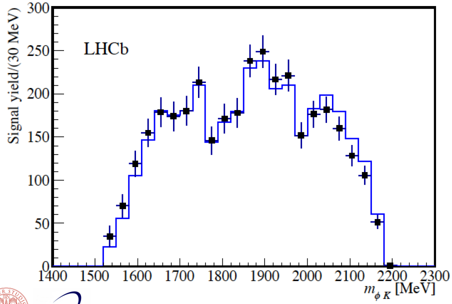
$B^+ \to J/\psi\,\phi K^+$ Dalitz plot

PRL 118 (2017) 022003

PRD 95 (2017) 012002







All previous results based on 1D projections

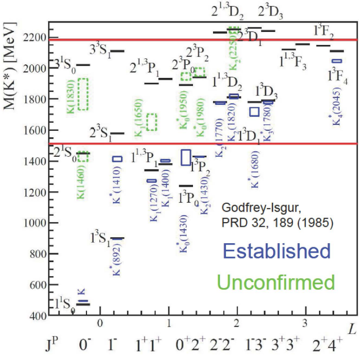
Need to understand reflections of interfering higher K^*

Amplitude fits

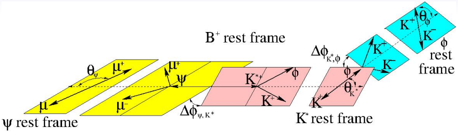
PRL 118 (2017) 022003
PRD 95 (2017) 012002

6D fit including K^* resonances + interfering NR background (0^{++} not allowed)

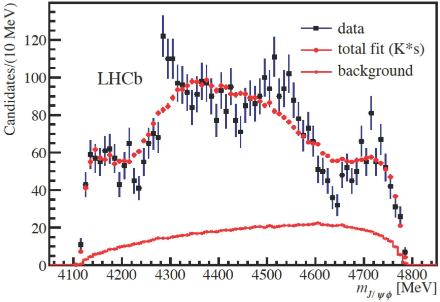
Experimental knowledge + predictions to choose the states to include in the model



masses and widths not constrained



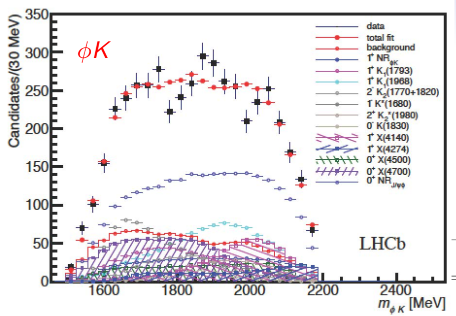
1-4 complex helicity terms per K^*

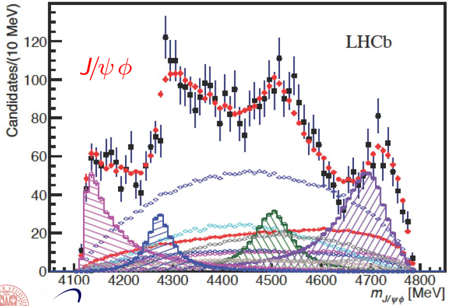


K^* resonances alone don't describe data

Fits allowing exotic components

PRL 118 (2017) 022003
PRD 95 (2017) 012002





Add X and Z^+ components with various quantum numbers

Z^+ components improve fit marginally

Two 1^{++} and two 0^{++} states with large significance

Contri-bution	Sign. or Ref.	Fit results M_0 [MeV]	Γ_0 [MeV]	FF %
All $X(1^+)$				$16\pm3\ ^{+\ 6}_{-\ 2}$
$X(4140)$	8.4σ	$4146.5\pm4.5\ ^{+4.6}_{-2.8}$	$83\pm21\ ^{+21}_{-14}$	$13.0\pm3.2\ ^{+4.7}_{-2.0}$
ave.	Table 1	4147.1 ± 2.4	15.7 ± 6.3	
$X(4274)$	6.0σ	$4273.3\pm8.3\ ^{+17.2}_{-\ 3.6}$	$56\pm11\ ^{+\ 8}_{-11}$	$7.1\pm2.5\ ^{+3.5}_{-2.4}$
CDF	[26]	$4274.4\ ^{+8.4}_{-6.7}\pm1.9$	$32\ ^{+22}_{-15}\pm8$	
CMS	[23]	$4313.8\pm5.3\pm7.3$	$38\ ^{+30}_{-15}\pm16$	
All $X(0^+)$				$28\pm\ 5\pm\ 7$
NR$_{J/\psi\phi}$	6.4σ			$46\pm11\ ^{+11}_{-21}$
$X(4500)$	6.1σ	$4506\pm11\ ^{+12}_{-15}$	$92\pm21\ ^{+21}_{-20}$	$6.6\pm2.4\ ^{+3.5}_{-2.3}$
$X(4700)$	5.6σ	$4704\pm10\ ^{+14}_{-24}$	$120\pm31\ ^{+42}_{-33}$	$12\pm\ 5\ ^{+\ 9}_{-\ 5}$

Significance of $J^{PC} = 1^{++}$ incl. syst.:
$X(4140)$: 5.7σ $X(4274)$: 5.8σ

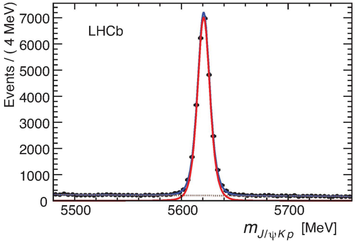
Significance of $J^{PC} = 0^{++}$ incl. syst. :
$X(4500)$: 4.0σ $X(4700)$: 4.5σ

$\Lambda_b^0 \to J/\psi p K^-$

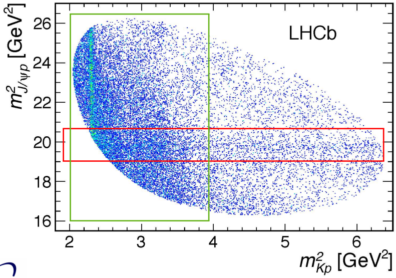
PRL 115 (2015) 072001

This decay mode, not observed before, found to have large rates and low background

Used to measure the Λ_b^0 lifetime with 1 fb^{-1} collected in 2011
PRL 111 (2013) 102003



Clean signal of 26,000 candidates with 5.4% background within $\pm 2\sigma$ in the whole Run 1 data sample (3 fb^{-1})



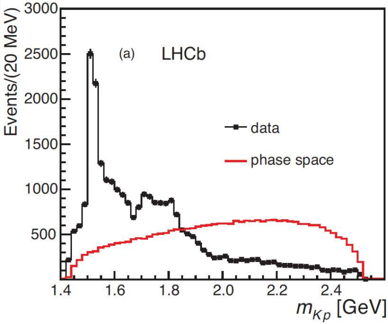
... but the Dalitz plot has unusual features:

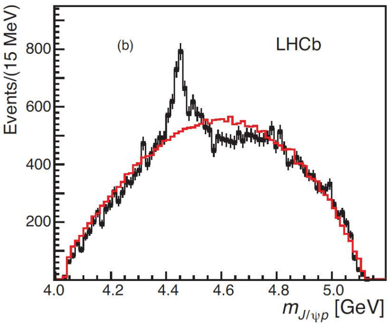
vertical bands for Λ^*'s

Horizontal band???

Dalitz plot projections

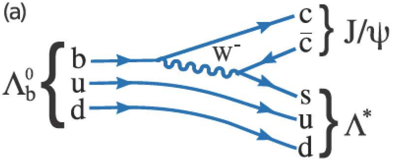
PRL 115 (2015) 072001

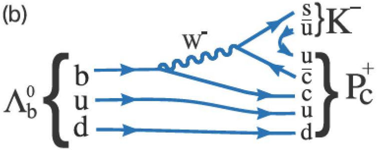




many $\Lambda^* \Longrightarrow$ Interference!

reflections from m(Kp)?
or exotic resonances???



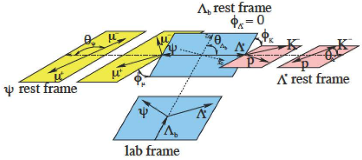


PRL 115 (2015) 072001

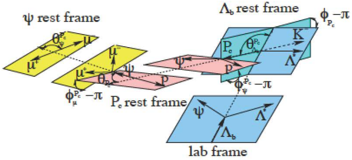
Amplitude Model

Six-dimensional amplitude fit: invariant mass, three helicity angles and two differences between decay planes. Allow for two interfering channels:

$\Lambda_b^0 \to J/\psi \Lambda^*$



$\Lambda_b^0 \to P_c^+ K^-$



all known Λ^* resonances (Extended)

or

just well motivated (Reduced)

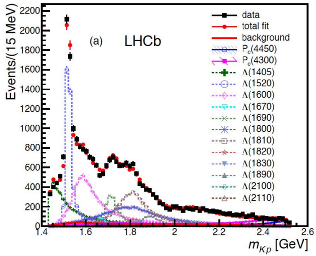
Angular distribution in helicity formalism

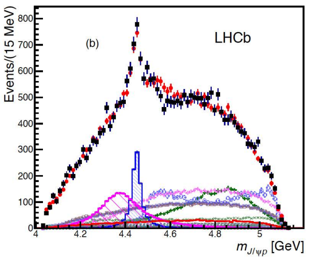
State	J^P	M_0 (MeV)	Γ_0 (MeV)	# Reduced	# Extended
$\Lambda(1405)$	$1/2^-$	$1405.1^{+1.3}_{-1.0}$	50.5 ± 2.0	3	4
$\Lambda(1520)$	$3/2^-$	1519.5 ± 1.0	15.6 ± 1.0	5	6
$\Lambda(1600)$	$1/2^+$	1600	150	3	4
$\Lambda(1670)$	$1/2^-$	1670	35	3	4
$\Lambda(1690)$	$3/2^-$	1690	60	5	6
$\Lambda(1800)$	$1/2^-$	1800	300	4	4
$\Lambda(1810)$	$1/2^+$	1810	150	3	4
$\Lambda(1820)$	$5/2^+$	1820	80	1	6
$\Lambda(1830)$	$5/2^-$	1830	95	1	6
$\Lambda(1890)$	$3/2^+$	1890	100	3	6
$\Lambda(2100)$	$7/2^-$	2100	200	1	6
$\Lambda(2110)$	$5/2^+$	2110	200	1	6
$\Lambda(2350)$	$9/2^+$	2350	150	0	6
$\Lambda(2585)$	?	$\approx$2585	200	0	6

Amplitude Model: results

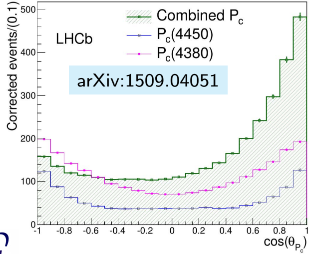
PRL 115 (2015) 072001

Two exotic states are required to obtain an adequate fit





Interference between two P_c of opposite parity required to explain the P_c decay angular distribution



The P_c parameters from the "reduced" fit are

	$P_c(4380)^+$	$P_c(4450)^+$
J^P	$\frac{3}{2}^-$	$\frac{5}{2}^+$
Mass [MeV/c^2]	$4380 \pm 8 \pm 29$	$4449.8 \pm 1.7 \pm 2.5$
Width [MeV/c^2]	$205 \pm 18 \pm 86$	$39 \pm 5 \pm 19$
Fit fraction [%]	$8.4 \pm 0.7 \pm 4.2$	$4.1 \pm 0.5 \pm 1.1$
Significance	9σ	12σ

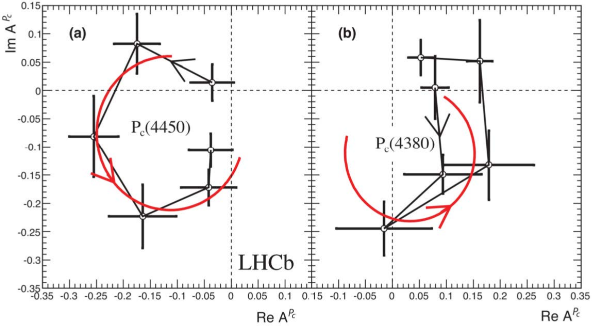
significance from pseudo-experiments (includes systematic)

The combined significance $> 15\sigma$

Resonance?

PRL 115 (2015) 072001

Real and immaginary part of the amplitude determined independently in 6 bins between $M - \Gamma$ and $M + \Gamma$

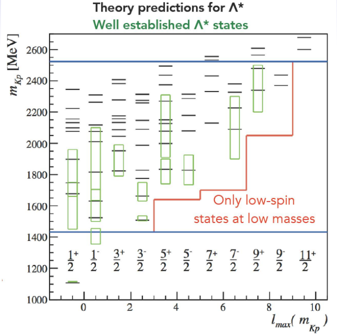


The $P_c(4450)$ amplitude shows a phase variation consistent with what expected for a Breit-Wigner resonance

Not conclusive for $P_c(4380)$

PRL 117(2016)082002

Model independent analysis of $\Lambda_b^0 \to J/\psi p K^-$

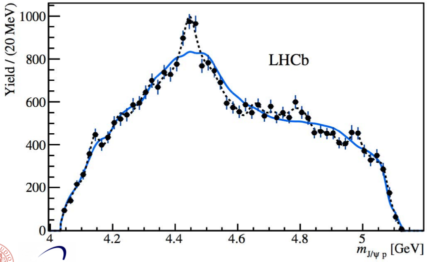


The $\Lambda*$ spectrum is the largest systematic uncertainty in the P_c observation

The NR $K^- p$ component could have non trivial mass-dependence

Model independent approach: no assumption on Λ^*, Σ or NR structure

Only restrict maximum spin of Λ^* component in each interval of Kp invariant mass



Compare $m(J/\psi p)$ in data to MC weighted as to reproduce $\Lambda^* \to Kp$ reflections based on angular moments

The hypothesis that data can be described by reflections of Kp structures is excluded at 9σ

Search for exotics in $\Lambda_b^0 \to J/\psi p \pi^-$

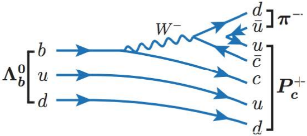
Cabibbo-suppressed – observed by LHCb **JHEP 1407 (2014) 103**

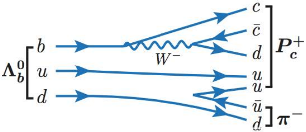
$$\frac{\mathcal{B}(\Lambda_b^0 \to J/\psi p \pi^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)} = 0.0824 \pm 0.0025\,(\text{stat}) \pm 0.0042\,(\text{syst})$$

Observing the same P_c^+ states in a different decay mode could indicate they are really resonances and not some kinematical effects

Wang et al; PRD 93 (2016) 094001

Cabibbo-suppressed Λ_b^0 decays to baryonic exotic resonances





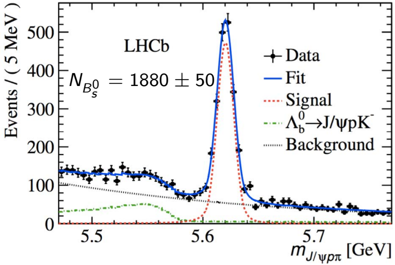
are predicted to have Cheng, Chua: PRD 92 (2015) 096009

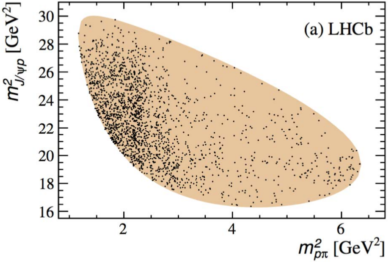
$$R_{\pi^-/K^-} \equiv \frac{\mathcal{B}(\Lambda_b^0 \to \pi^- P_c^+)}{\mathcal{B}(\Lambda_b^0 \to K^- P_c^+)} \approx 0.07 - 0.08$$

$\Lambda_b^0 \to J/\psi p \pi^-$

PRL 117 (2016) 082003

Similar candidates selection as for $\Lambda_b^0 \to J/\psi p K^-$, with additional vetos for specific background sources ($\bar{B}^0 \to J/\psi K^+\pi^-$, $\bar{B}_s^0 \to J/\psi K^+K^-$, $\Lambda \to K^+\pi^-$)





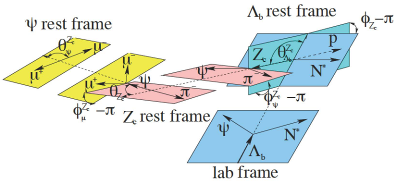
No striking features in the Dalitz plot, perform amplitude analysis

$\Lambda_b^0 \to Z_c^+ p$

As in the CF mode, six-dimensional fit to interfering amplitudes. In this case:

- $\Lambda_b^0 \to J/\psi N^*$
- $\Lambda_b^0 \to P_c^+ \pi^-$
- $\Lambda_b^0 \to Z_c^- p$

$Z_c(4200)^- \to J/\psi \pi^-$ reported by Belle in $B^0 \to J\psi K\pi$ PRD 90 (2014) 112009



Amplitude model fits to $\Lambda_b^0 \to J/\psi p \pi^-$

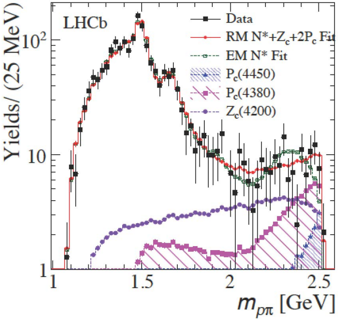
State	J^P	M_0 (MeV)	Γ_0 (MeV)	RM	EM
NR $p\pi$	$1/2^-$	-	-	4	4
$N(1440)$	$1/2^+$	1430	350	3	4
$N(1520)$	$3/2^-$	1515	115	3	3
$N(1535)$	$1/2^-$	1535	150	4	4
$N(1650)$	$1/2^-$	1655	140	1	4
$N(1675)$	$5/2^-$	1675	150	3	5
$N(1680)$	$5/2^+$	1685	130	0	3
$N(1700)$	$3/2^-$	1700	150	0	3
$N(1710)$	$1/2^+$	1710	100	0	4
$N(1720)$	$3/2^+$	1720	250	3	5
$N(1875)$	$3/2^-$	1875	250	0	3
$N(1900)$	$3/2^+$	1900	200	0	3
$N(2190)$	$7/2^-$	2190	500	0	3
$N(2220)$	$9/2^+$	2250	400	0	0
$N(2250)$	$9/2^-$	2275	500	0	0
$N(2600)$	$11/2^-$	2600	650	0	0
$N(2300)$	$1/2^+$	2300	340	0	3
$N(2570)$	$5/2^-$	2570	250	0	3
Free parameters				40	106

Include in the fit

- all known N^* (Extended)
- only well motivated (Reduced)

All L allowed

Limited sample size: fix P_c and Z_c parameters when testing if their amplitudes are required



The $m(p\pi^-)$ projection is adequately described by fits with N^* only

Exotic components seem not required

... but in a 6D fit differences may manifest only in restricted regions

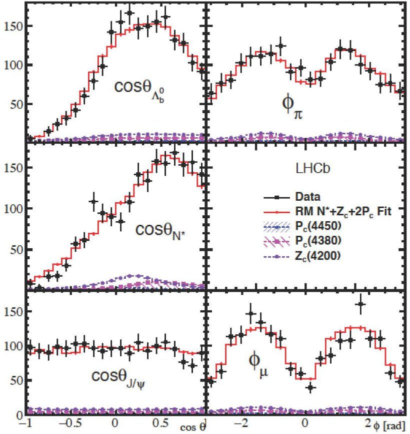
Evidence for exotic components in $\Lambda_b^0 \to J/\psi p\pi^-$

The N^*-only (extended) model does not describe data in all variable space

The reduced models with exotic (2 P_c or Z_c, or both) have acceptable fits in all variables

The significance (including syst) for $2P_c$ without Z_c is 3.3σ
None has individually large significance.

States	Fit fraction (%)
$P_c(4380)^+$	$5.1 \pm 1.5^{+2.1}_{-1.6}$
$P_c(4450)^+$	$1.6^{+0.8+0.6}_{-0.6-0.5}$
$Z_c(4200)^-$	$7.7 \pm 2.8^{+3.4}_{-4.0}$



Ratios of CS/CF for exotic components compatible with $0.07 - 0.08$ (albeit large errors!)

Cheng, Chua PRD 92 (2015) 096009

$$R_{\pi^-/K^-}(4380) = 0.050 \pm 0.016^{+0.020}_{-0.016} \pm 0.025$$
$$R_{\pi^-/K^-}(4450) = 0.033^{+0.016+0.011}_{-0.014-0.009} \pm 0.009$$

$$R_{\pi^-/K^-} \equiv \frac{\mathcal{B}(\Lambda_b^0 \to \pi^- P_c^+)}{\mathcal{B}(\Lambda_b^0 \to K^- P_c^+)}$$

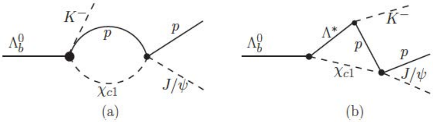
$P_c(4450)$: resonance or kinematical effect?

The $P_c(4450)^+$ lies just above the $\chi_{c_1}\, p$ threshold

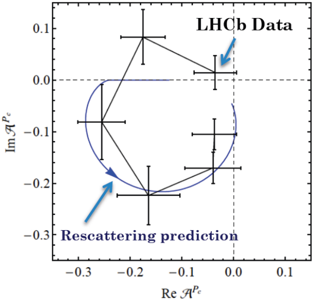
could be explained by kinematical rescattering effects

Meißner et al. PLB 751 (2015) 59

Guo et al. PRD 92 (2015) 071502



with current statistics the Argand plot cannot resolve the issue



Rescattering would not explain a narrow enhancement in $\chi_{c_1}\, p$